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Abstract. Interests on few-body hypernuclei have been increased by recent results of experiments employing relativistic heavy ion beams. Some of the experiments have revealed that the lifetime of the lightest hypernucleus, hypertriton, is significantly shorter than 263 ps which is expected by considering the hypertriton to be a weakly-bound system. The STAR collaboration has also measured the hypertriton binding energy, and the deduced value is contradicting to its formerly known small binding energy. These measurements have indicated that the fundamental physics quantities of the hypertriton such as its lifetime and binding energy have not been understood, therefore, they have to be measured very precisely. Furthermore, an unprecedented Λnn bound state observed by the HypHI collaboration has to be studied in order to draw a conclusion whether or not such a bound state exists. These three-body hypernuclear states are studied by the heavy-ion beam data in the WASA-FRS experiment and by analysing J-PARC E07 nuclear emulsion data with machine learning.

1. Introduction

There have recently been much attention in the field of hypernuclear and few-body physics on the lightest hypernucleus, the hypertriton, regarding its lifetime and binding energy. The hypertriton was experimentally studied until the 1970s by using nuclear emulsions and bubble chambers, which concluded that a Λ hyperon is very weakly bound to a deuteron core with a small binding energy of 0.13 ± 0.05 MeV [1, 2]. This precise information on the binding energy has been a very important input for constructing theories for hypernuclei, thus it has been regarded as benchmarking information in the hypernuclear physics. Contrary to the precised measured binding energy, the lifetime of the hypertriton was not precisely determined until the 1970s, and it has been considered to be very close to the lifetime of a free Λ hyperon, i.e., 263 ps [3], without having any evidences. Recently, experiments with induced reactions of and collisions of heavy-ion beams have made precise measurements of hypertriton lifetime be possible, and all recently published values are summarised in Table 1. Very recently, the STAR collaboration performed the combined analysis for all the published hypertriton lifetime values, and it has been concluded on the deduced weighted averaged value to be 200 ± 13 ps which is considerably lower than that of the Λ hyperon [9]. On the other hand, as shown in Table 1, the measured values have a large span for measured values obtained even by one collaboration. Furthermore, the precision of the current measurements is not sufficient to draw a conclusion for the value of the hypertriton lifetime. Thus, at least one measurement with an excellent accuracy is awaited to clarify the situation. It has been discussed that the binding energy of the hypertriton could strongly be correlated to its lifetime. After the binding energy was deduced by employing nuclear emulsions in 1968 [1] and 1973 [2], additional experimental studies were never performed until recently for the hypertriton binding energy. However very recently, the STAR collaboration measured the binding energy of the hypertriton B_Λ to be 0.41 ± 0.12(stat.) $\pm$ 0.11(syst.) MeV [12]. Surprisingly, this value is significantly larger than the previously known binding energy of 0.13 ± 0.05 MeV from the nuclear emulsions. On the other hand, the accuracy of the STAR result is not sufficient enough to reach a solid conclusion. The ALICE collaboration recently deduced a smaller binding energy of $72\pm63\pm36$ keV [13], however, this small value has not been reproduced by other experiments.

Another type of three-body hypernuclear states have also become being of special interest. The HypHI collaboration observed an indication of signals in the invariant mass distributions of the d+π^- and t+π^- final states, which may indicate a possibility of existence of an unprecedented neutral bound state formed by a Λ hyperon and two neutrons, i.e., Λnn [14]. Many theoretical efforts were made to study this state within various theoretical approaches and models [15, 16, 17, 18]. However, the obtained results did not show a possible Λnn ibound state. On the other hand, it should be noted that pionless effective field theory studying the Λnn state with $I = 0$ has not ruled out the bound state [19, 20]. Possible resonance states associated with the Λnn state have also been studied theoretically [18, 21]. Very recently, the E12-17-003 experiment at JLab was performed for searching for Λnn bound and resonance state by employing electron beams to bombard a tritium target. They have observed an indication of the existence of states probably related to Λnn with small significance [22]. On the other hand, the same collaboration published different interpretations of the data, which suggest non-existence of Λnn [23]. Therefore, a conclusion has not been reached yet by the results of the E12-17-003 experiment. The existence of the Λnn should be further studied experimentally with better precision and more data samples.

This contribution will focus on our approaches for studying the hypertriton and the unprecedented Λnn state by means of heavy-ion beams, nuclear emulsion and machine learning [24].

2. The WASA-FRS experiment with heavy-ion beams

The WASA-FRS experiment has employed the GSI fragment separator (FRS) [25] as a high momentum-resolution forward magnetic spectrometer, and one of subjects of the experiment is to study light hypernuclei including the hypertriton and Λnn. Figure 1 shows a schematic layout of the FRS. The WASA central detector [26] is mounted at the mid focal plane (F2) of the FRS. The WASA central detector is composed by a superconducting solenoid magnet (up to 1 T) with its associated iron yokes and a cryogenic cooling system, a CsI(Na) calorimeter, inner drift chambers with straw tubes, and newly developed plastic barrel hodoscope arrays [27] and plastic end-cap hodoscopes. We have also developed six scintillating fibre detectors and a start counter for Time-of-Flight measurements dedicated to the hypernuclear experiment with the WASA-FRS setup. The WASA-FRS experiments [24] aims at studying the hypertriton ($^3_\Lambda$H), $^4_\Lambda$H and Λnn production, and it employed beams of ^{6}Li at 2 A GeV for producing hypernuclei of interest. Beams were delivered to the F2 area of the FRS, and hypernuclei of interest are produced inside the target mounted in front of the WASA detector. We aim at measuring the following decay channels; $^3_\Lambda$H$\rightarrow$ π^-+^{3}He, $^4_\Lambda$H$\rightarrow$ π^-+^{4}He and Λnn $\rightarrow$ π^-+d+n (without measuring n). Residual nuclei produced by these hypernuclear decay with the emission of a

Table 1. Summary of the measured hypertriton lifetimes obtained by the HypHI, the STAR and the ALICE collaborations. The values are shown with their statistical and systematic uncertainties.

Exp.	Reaction and energy	Prod. meth.	Lifetime [ps]	Year of pub.
HypHI at GSI	^{6}Li+^{12}C at 2 A GeV	Projectile fragmentation	$183^{+42}_{-32} \pm 37$	2013 [4]
STAR at RHIC	^{197}Au+^{197}Au at $\sqrt{s_{\rm NN}} = 200$ GeV	Central collision	$182^{+89}_{-45} \pm 27$	2010 [5]
			$155^{+25}_{-22} \pm 31$	2017 [6]
			$142^{+24}_{-21} \pm 29$	2018 [7, 8]
	^{197}Au+^{197}Au at $\sqrt{s_{\rm NN}} = 3$ & 7.2 GeV		$221^{+15}_{-19} \pm 27$	2022 [9]
ALICE at the LHC	^{208}Pb+^{208}Pb at $\sqrt{s_{\rm NN}} = 2.76$ TeV	Central collision	$181^{+54}_{-39} \pm 33$	2016 [10]
	^{208}Pb+^{208}Pb at $\sqrt{s_{\rm NN}} = 5.02$ TeV		$242^{+34}_{-38} \pm 17$	2019 [11]

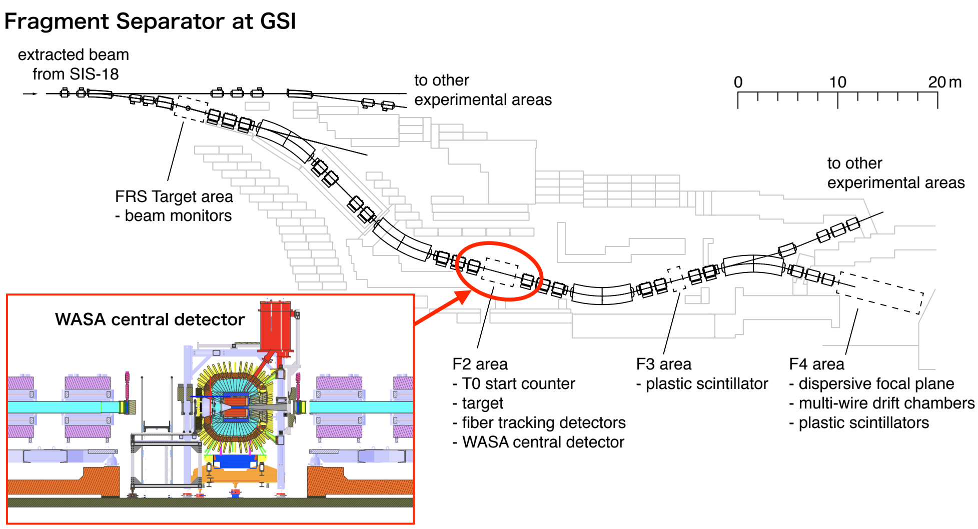

Figure 1. The Fragment Separator (FRS) and the WASA detector at the F2 area.

π^- meson are forward boosted, and therefore, approximately 10% of the residual nuclei from these hypernuclear decay fall within the acceptance of the FRS behind the exit of the F2 area, and they are transported through the final focal plane (F4) of the FRS. On the other hand, π^- mesons produced by these hypernuclear decays are widely emitted in the F2 area, and they are measured by the WASA detector with additional detectors at F2.

According to Monte Carlo simulations [24], the signal integral was estimated to be approximately 5.8×10^3 with a significance of approximately 120 σ. In comparison to the former HypHI experiment, the peak integral has been increased by a factor of approximately 38, and the significance is expected to be approximately 25 times higher [4]. The peak width is also estimated with Monte Carlo simulations and is ~ 3.18 MeV. This width is 1.5 times narrower than that observed in the HypHI experiment [4]. The accuracies for the lifetime have also been investigated by simulations. Estimated values are different for lifetime values, and they are 5 ps, 8 ps and 13 ps for lifetime values of 150 ps, 200 ps and 250 ps, respectively. We also studied feasibilities on observing the Λnn state, and the measurement can reach a similar performance

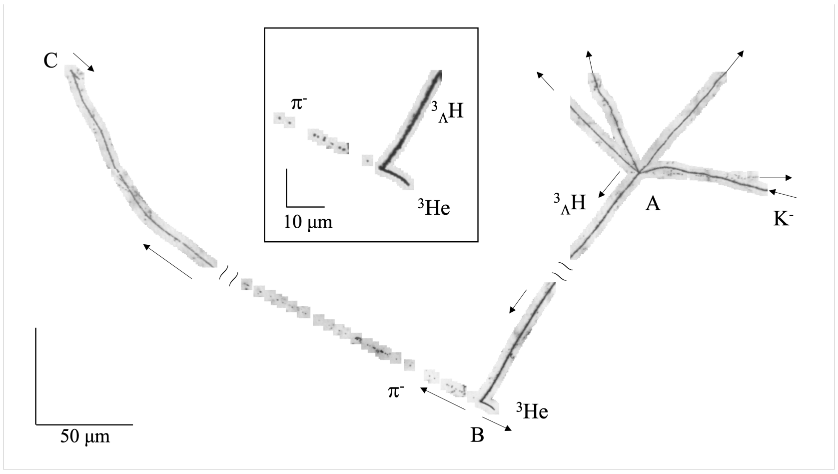

Figure 2. The first discovered hypertriton event in the nuclear emulsion of the E07 experiment at J-PARC [24]. A K^- meson that is most probably a scatted beam enters the emulsion sheet from outside the emulsion modules, and then it propagates to the point A. The K^- meson is stopped there and is absorbed by one of nuclei in the emulsion to produce four visible nuclear fragments and one $^3_\Lambda$H. The hypertriton ($^3_\Lambda$H) peneterates towards the point B, where it stops. The hypertriton decays into the ^{3}He and π^- final state. The inset of the figure presents a magnification figure around the decay point B.

of the hypertriton measurement.

The WASA-FRS experiment to study the hypertriton, $^4_\Lambda$H and Λnn was already performed at GSI in the first quarter of 2022 with ^{6}Li projectiles at 2 A GeV bombarding a diamond target with a thickness of 9.87 g/cm^2. The data analysis is in progress, and particle identification by the WASA detector and the FRS have already been made successfully [28].

3. Precise measurement of the hypertriton binding energy with nuclear emulsion and machine learning

To measure the binding energy of the hypertriton at the best precision, we re-analyse the existing J-PARC E07 nuclear emulsions by employing machine learning techniques. It enables us to handle large data sample and thus to reach the best possible precision. The J-PARC E07 experiment [29] was performed in 2016–2017, and it employed approximately 1300 dedicated nuclear emulsion sheets. They were irradiated by intense K^- beams, and data analyses to search for double-strangeness hypernuclei by using the so-called hybrid method [29] were already completed. In the same experiment, hypertritons were also produced by induced reactions of K^- beams on nuclei inside the nuclear emulsions, and their events (production and decay) of produced hypertritons are also recorded. However, in order to discover hypertritons in the E07 nuclear emulsions, a complete scan of the entire emulsion volume for all the sheets is necessary since signals associated with the hypertriton production are not recorded.

We aim at detecting hypertriton decay from a stopped point at rest via the two-body decay of hypertriton, i.e., ^{3}He+π^-. The observed event is used to determine the invariant mass for deducing the binding energy. The advantage of using the two-body decay event into ^{3}He+π^- (a hammer-like event) is that the track length of the π^- meson is well defined only by the two-body decay kinematics. For this case, it is approximately 28 mm. This length is fortunately very unique and very different for the other hypernuclear decays. For example, the π^- track length for the case of $^4_\Lambda$H is approximately 42 mm, almost 14 mm longer than that from the hypertriton decay. Therefore, we can achive a firm identification of the hypertriton event without ambiguity and background. On the other hand, analytical image processing can hardly classify these hammer-like shapes with high efficiency and large background suppression, since the shape of the hypertriton decay event is too simple and since an associated π^- track is very sparse. Therefore, the classification requires human visual inspection with the existing technology and conventional methods in former emulsion analysis. Our estimations show that there should be approximately 1.4 billion images per emulsion sheet to be inspected by human eyes, hence it should take about 560 years to analyse all the emulsion sheets with ten people [24]. Furthermore, a signal to background ratio is estimated to be only $\sim 10^{-7}$. Because of the huge human load and the extremely small signal-to-background ratio, hypertritons were never observed so far in the data of the E07 [29] experiment, and there were either no hypertriton event observed in the former experiments at KEK.

To overcome these difficulties, we have developed a novel technique with machine learning to detect candidates for hypertriton events in the E07 nuclear emulsion data [24]. The first difficulty in the development is that there is no real training data with hypertriton events because no hypertriton event was observed in the E07 nuclear emulsion. We employed Monte Carlo simulations for creating data surrogating real production and decay of the hypertriton in the emulsion material. The Monte Carlo simulations can provide sharp lines as particle trajectories, and these need to be transferred to defused line shapes like track images in the real emulsion by considering the size of silver grains in the emulsion and the optical conditions of the micro scope in the measurements. We have achieved it by employing one of the machine learning techniques, the so-called Generative Adversarial Networks (GANs) [30]. To create training data surrogating real emulsion images, background images are taken randomly from the part of the real emulsion data and mixed with the transferred defused lines to imitate hypertriton events in the nuclear emulsion. With this new technique, we produced a sufficient amount of training data for developing the machine learning models for detecting hypertriton events with the two-body decay channel. We have already developed a machine learning model for detecting hypertriton events with the Mask R-CNN [31]. Surrogated images mentioned above are employed for training the object detection model with the Mask R-CNN. For the analysis, we used the dedicated automated microscope scanning devices for scanning the emulsion sheets of the E07 experiment, and then all the raw images are recorded on a storage disk. We attempted to detect tracks of interest within real emulsion images by applying the trained machine learning models to the stored data. We have already established the analysis procedure and the number of the discovered hypertriton decays increases daily. We discovered the first hypertriton event on February 2nd in 2021 [24, 32], and it is shown in Figure 2. It should be noted that only approximately 0.9% of the total emulsion data (1300 sheets) were analysed until August 25th in 2022, and we detected already approximately twenty hypertriton events In the same analyses, we also discovered and identified four times more ${}^{4}_{\Lambda}\mathrm{H}$ events. Our current situation on the analysis of the E07 emulsion data guarantees the improvement in the accuracy for the determination of the hypertriton binding energy in near future. We have also estimated the systematic uncertainty for the determination of the hypertriton binding energy to be 28 keV by revisiting the former emulsion data and by employing Monte Carlo simulations [33]. This uncertainty is to be improved by means of our new calibration technique on the density of nuclear emulsions [32]. In the nuclear emulsions, there are cow gelatines that contains natural radioactive elements, and we employ one of useful radio active chains for calibrating the density and the shrinkage factors of the emulsion is thorium (Th) α-decay series. We measure track length of the α-particle at 8.787 MeV from the decay channel of ${}^{212}\mathrm{Po}\rightarrow{}^{208}\mathrm{Pb}+\alpha$, and It is used to calibrate the density and the shrinkage factor of the emulsion. We already collected thousands of events of Th decay chains by visual inspections in prior to the current machine learning developments,, and these events will be used to evaluate the performance of our developed models with the Mask-R CNN, and it is currently in progress. Our projects are in progress also for searching for three-body decay events, therefore, the binding energy of, for example, ${}^{4}_{\Lambda}$He and ${}^{5}_{\Lambda}$He will be precisely determined [34]. Search for more double-strangeness hypernuclei with the developed method is also in progress [34].

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